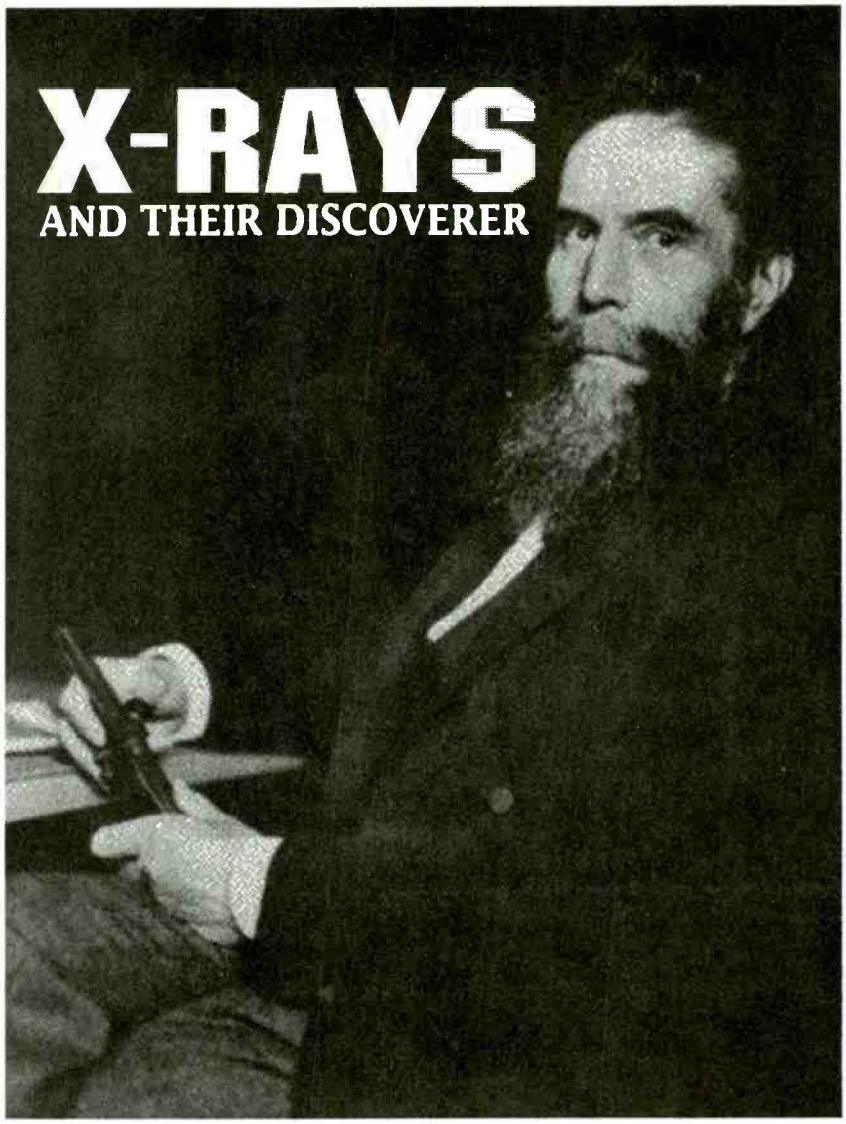
X-RAYS AND THEIR DISCOVERER



A hundred years have passed since Wilhelm Konrad Röntgen discovered X-rays, but new applications in science, medicine, electronics and industry continually still keep popping up.

LUTHER STROUD AND NEIL SCLATER

"HUNCH YOUR SHOULDERS FORward, take a deep breath—and don't breathe or move! Ready?" This is what you hear from your physician or a technician before the buzz and click that tells you invisible rays have passed through your body and impinged on photographic film. Having X-ray pictures taken at a physician's or dentist's office is the way most people are deliberately exposed to this high-frequency radiation—and then for only a fraction of a second.

The large X-ray negative tells the physician a lot about your heart, lungs and other internal organs. No needles, tongue depressors, chest thumping, or other invasive procedures. And it tells a lot about the properties of X-rays—their ability to penetrate cloth, paper and flesh to reveal, in shadowy outline, the presence of disease, the location of bone fractures or the presence of foreign bodies.

But there is nothing new here, you say, you knew all this. Most of us take the X-ray exam for granted, and could not visualize modern medicine without it. So why raise the subject at this time? The answer is that X-rays were first discovered, quite by accident, one hundred years ago this month.

What is more, the role for X-rays is still expanding from its original—and perhaps still most important one— in medical diagnostics. However X-rays are also used to treat cancers, analyze materials, detect contraband, inspect the quality of welds, and even reveal more about the universe. Although still in the experimental stage, X-ray lithography holds promise for sub-micrometer, high-density integrated circuit fabrication. And, don't forget the X-ray television and X-ray lasers.

Serendipitous discovery

On November 8, 1895, physics professor, Wilhelm Konrad Röntgen (often Anglicized to Roentgen) (1845 - 1923), was working in his laboratory at the Physical Institute at the University of Wurzburg, Germany, trying to duplicate and understand the results of experiments done by others in the emerging field of electrical conduction through a vacuum or gas.

Professor Röntgen knew what the others had accomplished, and he had all of the apparatus needed to permit him to duplicate their findings. Fortunately for science, medicine, and mankind, he was a trained scientist who quickly recognized the value of his discovery and lost no time in trumpeting it to the world. But before saying more about how Dr. Röntgen discovered, X-rays, the work of the other scientists, principally English and German, should be

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put in perspective so you can appreciate the fortuitous circumstances surrounding his discovery.

Perhaps you recall reading about Heinrich Geissler (1814 - 1891), a German instrument maker, master glass blower, and physicist from the article "Seeing the Unseen" in the October 1995 *Electronics Now*. In the 1850s Geissler invented a gas-filled, light-emitting tube that produced a controlled, continuous source of bright light. He accomplished what he set out to do—develop a source of continuous light for spectroscopy, but later it was found that his tube could be pulsed. It became the ancestor of the modern flashlamp.

Geissler also contributed to the development of the modern vacuum pump, necessary equipment for evacuating closed tubes for all experiments in electron conduction through vacuum and gas tubes. About that same time, the English physicist Michael Faraday (1791-1867), best known for his pioneering work in electromagnetic induction and the discoverer of the basic principles of the electric motor, was also investigating electricity in gas-filled tubes.

Others active in the field at the time were the German physicists Johann Wilhelm Hittorf and Julius Plucker. Hittorf named the mysterious flow of electricity in tube "cathode rays," but we now know that they were really streams of electrons. During the next 20 years Plucker, Hittorf, and others in Germany revealed most of the important characteristics of ionized gas and cathode rays.

To carry out their experiments, those scientists needed power supplies. Most started off by wiring large batteries in series, and some even tried friction machines. Eventually they turned to the battery-powered induction coil. It was compact, portable, and easily controlled by a switch in the primary circuit. During the 1850s, another German instrument maker, Heinrich Ruhmkorff, improved the coil by separating the primary and secondary coils with a glass bobbin. Later interrupters, formed by moving wires in and out of a mercury pool, were installed for switching the primary windings.

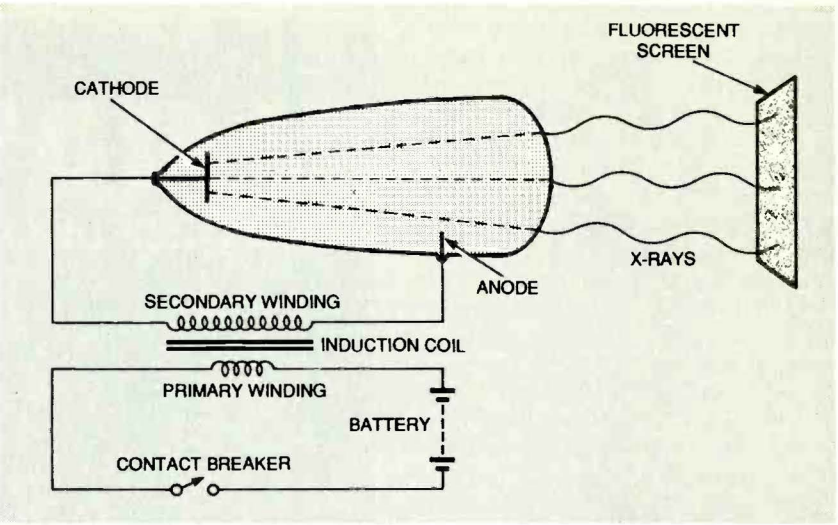

FIG. 1—A CROOKES tube with a power supply consisting of a battery and a coil. X rays emitting from the right end of the tube will cause a screen coated with barium salts to fluoresce.

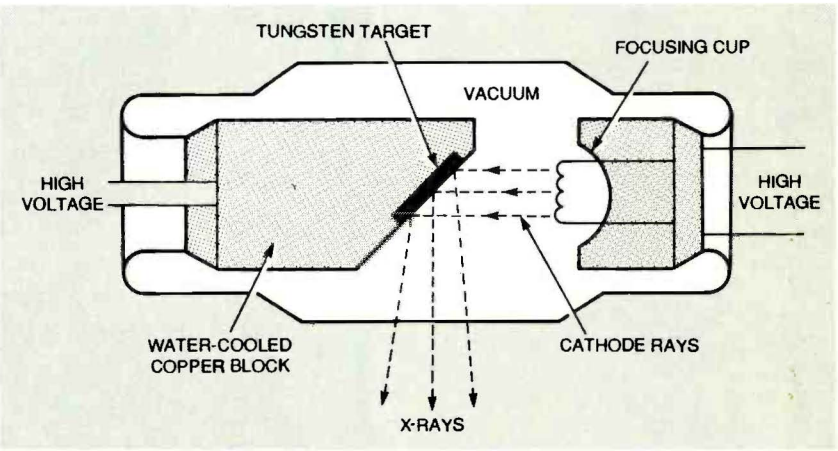

FIG. 2—A MODERN X-RAY TUBE contains a heated cathode that emits electrons and a tungsten anode. The X rays are focused by the bevel to the side of the tube. A heavy water-cooled radiator dissipates the heat generated by electron bombardment.

In 1875 the English physicist, Sir William Crookes (1832 - 1919) improved on the Geissler tube, and in 1879 he demonstrated peculiar glow phenomena by passing current through a cathode tube that contained traces of gas. Crookes found that if the air pressure in the tube is reduced by a vacuum pump to about 1 centimeter of mercury, a thin bright streamer can be seen between the anode and cathode of the tube. Its color depends on the gas in the tube.

As the pressure is lowered further, the streamer is replaced by a bright column of light filling the whole space between the electrodes. This was the stage reached in Geissler tube and in modern neon and argon lamps. If the pressure is reduced further to about 1 millimeter of mercury, the positive space shrinks and dark spaces appear.

Finally the column disappears entirely, and the pressure at about 0.001 millimeter of mercury the walls of the tube glow with a greenish light (*fluorescence*). Crookes did not know it then, but this stage must be reached to cause X-ray radiation. The phenomena pro-

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X-RAYS

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duced also depends on the size of the tube and the impressed voltage. However, Crookes discovered that the cathode rays could cast a shadow on fluorescent material at the end of the tube.

Crookes' demonstrations inspired other scientists to experiment with cathode rays passing through glass tubes with partial vacuums, gas, and combinations of these. The flow of electricity in the Crookes tubes was initiated by an induction coil. Figure 1 is a simplified diagram of the tube and its power supply. The electrons that formed the current originated at the cathode and passed through the partial vacuum to the anode.

Ironically, photographic plates that Crookes kept in his laboratory were mysteriously fogged and ruined, although they were in protective containers, but he never knew why. Thus, he missed his opportunity to discover of X-rays. The effects he produced could not be explained with the physics of the day—much as science today cannot explain the phenomena known as ball lightning.

Now back to Professor Röntgen. On that fateful day in 1895, he set out to study discharge from a Crookes tube so he could explain the phenomena. His apparatus was the same as that used by Crookes (shown in Fig. 1), and it included a Ruhmkorff coil. Because the Crookes tube glowed slightly when the current flowed, Röntgen darkened the room to see the glow better. He also covered the end of the tube with black cardboard to block the cathode rays.

However, much to his annoyance he noticed a fluorescent glow from a sheet of paper coated with a barium salt across the room. He looked around for the cause of the fluorescence and saw only that the Crookes tube was operating. But the end of the tube was still covered. He shut off the power and saw that the glow of the paper faded. and the room was dark again.

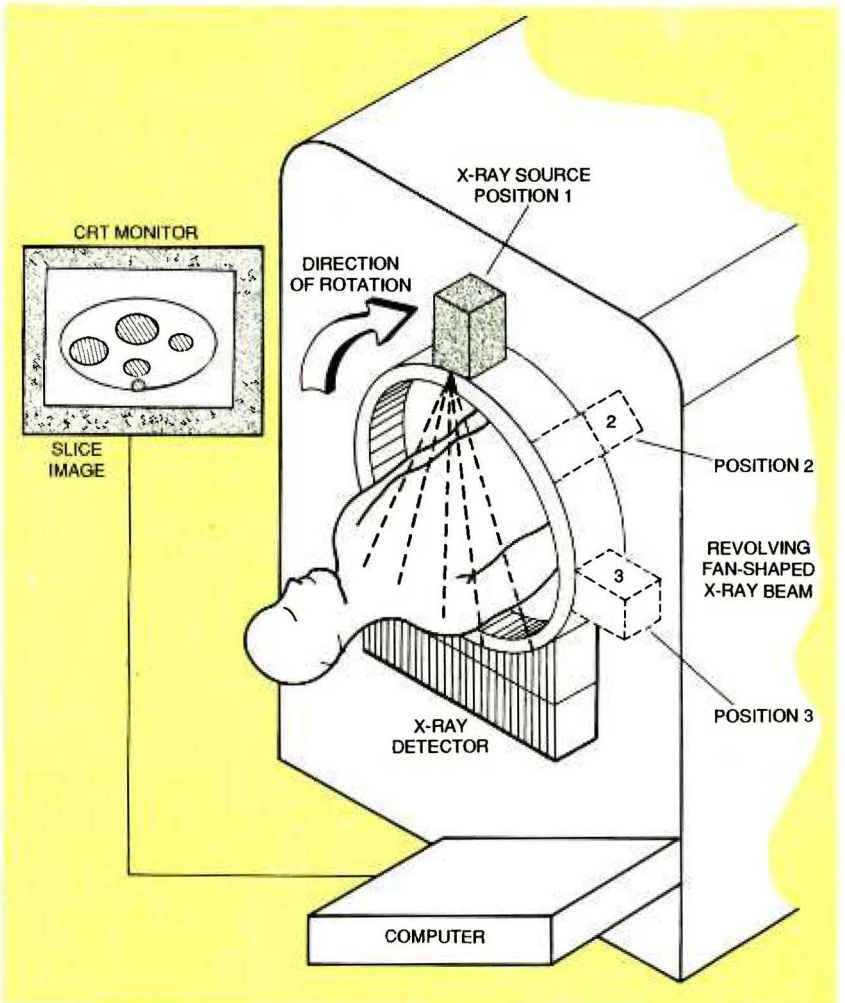

FIG. 3—A COMPUTED TOMOGRAPHY SYSTEM has an X-ray scanner that revolves around the patient. Data taken from the scanner is processed by computer to form a cross-section image of a "slice" of the human body, eliminating X-ray shadows.

After turning the tube back on the greenish glow reappeared. He put a book in front of the tube and the paper still glowed. Then he replaced the book with a block of wood and even used rubber as a shield, but the strange radiation passed right through. He then put a box of laboratory weights in front of the tube and found that dark silhouettes of the weights showed up on the paper screen.

Finally, he placed his hand between the tube and distant coated paper and was astonished to see the faint outline of the flesh of his hand and the dark outline of the bones. Next, he made the first intentional X-ray photograph by asking his wife to put her hand between the tube and a photographic plate. That's when he knew he was on to something.

His observations drove Dr. Röntgen to carry out more experiments to confirm that what he saw actually happened and could be reproduced. The Crookes tube was indeed the source of the mysterious invisible rays. Because, at the time, he could not explain them, he called them X-rays. At the end of December in 1895 Professor Röntgen submitted his first paper on the mysterious rays.

In January of 1896 Professor Röntgen gave the first public demonstration of X-rays. Soon scientists in laboratories around the world had duplicated his results. More than a thousand scientific articles were published on X-rays within a year of their discovery!

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Although Professor Röntgen never became wealthy as a result of his discovery, he did gain the recognition of the world's scientific community. In 1901, Dr. Röntgen became the first physicist to receive a Nobel prize. However, in 1903 a French scientist, Antoine Becquerel, also received a Nobel prize for the discovery of *natural radiation*. Today this term means radioactivity and it includes alpha, beta, and gamma rays. Gamma rays are more energetic than X-rays and they generally have shorter wavelengths and higher frequencies. Otherwise, they have the same general characteristics.

X-ray apparatus

Figure 1 shows that the Crookes tube was pretty simple. It was, in effect, a vacuum tube diode without a plate. Electrons emitted from the cathode are accelerated by the charge on the anode, which in his tube was only a wire. Thus, some of the radiation bypasses the small anode and exits through the end of the glass tube. If the voltage on the anode is high enough, X- rays will be produced by the collision of electrons with the glass of the tube.

Figure 2 is a simplified diagram of a modern X-ray tube. When high-speed electrons strike a massive target such as one made of lead or tungsten, X rays are generated. This X-ray tube contains a heated cathode that emits electrons as in most vacuum tubes and the anode target, typically made of tungsten embedded in a water-cooled copper block. The tungsten resists the destructive effects of heat caused by the energetic electron bombardment. The anode surface is beveled to deflect the X rays, and the gap between the cathode and the anode is only a few inches.

The heated cathode emits electrons, and the anode has a positive voltage. It is essentially a vacuum-tube diode. A high-voltage power supply accelerates the electrons which strike the anode at an angle of about 45°. As a consequence, X rays are scattered in all directions, but most focused into a cone whose axis is at right angles to the centerline of the tube.

Conventional X ray radiograms view the body from only one angle. The rays are absorbed (shadowed) by dense objects like bones, artificial joints, and metal foreign objects. However, the softer tissues—muscles, organs, and skin are more easily penetrated. X-ray films or radiograms represent the amount of X-ray penetration with different gray (intensity) levels.

Over the past 20 years, the introduction of image-intensifier technology in X ray machines has permitted a significant reduction in the duration and intensity the X-ray to which the patient are exposed without sacrificing picture sharpness and quality.

Some new X-ray systems include electronics that can scan and digitize the image and send signals to a closed circuit television set for such functions as real-time inspection of welds without endangering the operator of the inspection equipment.

Some X-ray systems include electronics that can scan the image and, by means of Xerography, produce an instant picture on paper. This saves the time lost and expense of manually developing a photographic film. These systems are not like-

WHAT ARE X-RAYS?

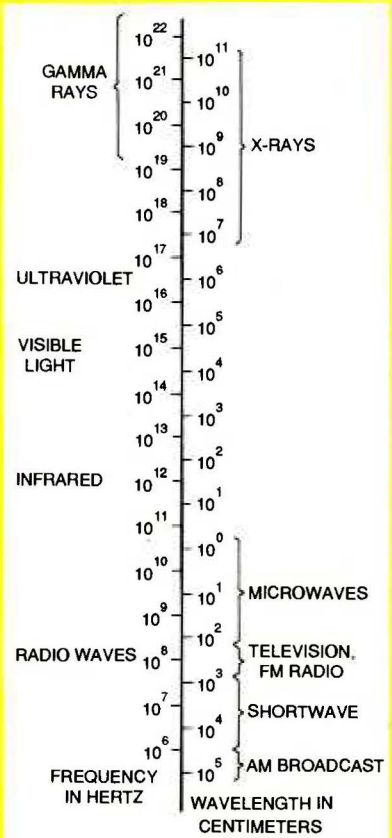
X-rays are electromagnetic radiation with properties similar to light, but with much shorter wavelengths (from about 10 -7 to 1-10 centimeters or 0.1 to 100 angstroms). These wavelengths are shorter than ultraviolet but not as short as some gamma rays at the far end of the spectrum. There is some overlap in frequency and wavelength between gamma and X rays. Longer wavelength X-rays are termed "soft" and shorter wavelengths are termed "hard."

X-rays are usually generated by accelerating electrons to a high velocity and suddenly stopping them by collision with a metal target. The resulting bombardment of the atoms in the target causes the atoms to lose energy, and this energy is radiated as X-rays of a definite wavelength.

Gamma rays behave essentially the same way as X-rays, but they have higher energy. Grouped with alpha (positive) and beta (negative) rays, they are considered to be *natural rays* that radiate from radium, uranium, and other natural substances. By contrast X-rays are considered to be *man-made* because they can be derived from tubes, synchrotrons and even lasers. X rays are produced when a stream of electrons strikes a target. This was the glass tube in the Crookes tube and is the tungsten anode in the modern X-ray tube.

X-rays propagate through a vacuum in the same way and at the same speed as other forms of electromagnetic radiation, including visible light. However, X-ray photons contain a considerable amount of energy, giving them exceptional penetrating power in comparison with visible light and radio waves.

X-rays, like ultraviolet rays and gamma rays, can cause severe burns and even cancer. Lead shields provide the usual protection against the frequencies and strengths of X-rays encountered in hospital and dentist and phsician offices. Nevertheless, carefully controlled X-rays are used to treat cancers.



ELECTROMAGNETIC SPECTRUM showing the position of X-rays with respect to ultraviolet and gamma rays at the far end of the spectrum.

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ly to replace conventional X-ray equipment because there is a tradeoff in detail. However, they can cut the cost of routine physical exams, and they can be lifesavers in situations where surgeons are treating severe trauma victims. No time is lost waiting for a negative to be developed.

Directions in X-ray technology

One of the most innovative X-ray systems developed within the past 25 years is computer-aided tomography, now generally called computed tomography (CT). This system, a marriage between the X-ray machine and a computer, converts signals generated by X rays into video images of a cross section of a patient. Figure 3 is a simplified diagram of the system showing its principal component, an X-ray source and detector array mounted on a scanning ring that so they revolve 360 ° around the patient is a single plane.

The patient is placed within the frame as shown in Fig. 3. The X-rays are focused in a thin fan-shaped beam that penetrates the patient's body. When the circular frame rotates, all sides of the patient are exposed to X rays. The sensitive detectors opposite the source convert the changing patterns of radiation received from the scanner into digital signals. A computer with a specialized applications program processes the data from the detectors and compares the views from many source positions to create a single video image on the monitor. The monitor presents a cross section or "slice" view of the patient's body. Because all sides of the internal bones, organs and tissues are exposed to X rays, no parts of the body are in "shadow." The patient can be positioned inside the scanner so images can be taken from head to foot. Multiple images permit the creation of 3-D images.

The later development of magnetic resonance imaging (MRI), based on the phenomenon of nuclear resonance, has stolen some of the thunder from computed tomography. However, the systems do not perform the same functions. Thus, the images gained from one can supplement the images obtained from the other to provide additional information valuable to surgeons performing certain critical operations. CT and MRI images can even be superimposed.

X-ray lithography

X-ray lithography is a process for transferring mask patterns to a resist-covered semiconductor wafer as an alternative to the more conventional ultraviolet-light lithography. It is also an alternative to electron-beam lithography. The shorter X-ray wavelengths of 10 to 50 angstroms vs. 2000 to 3000 angstroms for ultraviolet light minimize diffraction and extend the useful range of lithography toward the goal of 0.1 micrometer features on integrated circuitry. Optical lithography is expected to reach its limit at feature sizes shorter than 0.25 micrometer.

IBM, Motorola, and several Japanese electronics giants are actively developing synchrotron-based IC fabrication. Synchrotrons are X-ray sources that are expected to cost between $25 and $50 million. The magnetic fields of the synchrotron accelerate subatomic particles such as electrons and positrons to speeds that approach that of light. The speeding particles emit X-rays when the magnetic field lines are perpendicular to the direction of the particles.

X-ray equipment manufacturers and at least three laboratories are developing lower-cost sources of X-rays than synchrotrons. They will be equipped with hardware to reflect, collimate, and manipulate X-rays for chip fabrication.

Multiple application

X-ray diffraction is a phenomena used in the study and identification of materials. A beam of X-rays is diffracted when passed through the regular lattice structure of crystals. Characteristic diffraction patterns can be obtained for each crystalline material in the form of curved lines on photographic film.

An X-ray fluroescence absorptiometer measures the thickness of plating such as tin on steel. The primary X-ray beam is directed at the coating, causing the base metal to fluoresce. The resulting secondary radiation from the fluorescence is partially absorbed by the coating, giving an indication of its thickness.

X-ray spectrometers are instruments that direct X-rays at material specimens and measure the wavelengths of the various components of those materials for analysis. X-ray thickness gages measure the thickness of moving materials such as sheet steel during processing without making contact with the sheet. An X-ray beam directed through the sheet is absorbed in proportion to thickness of the material

Directions in X-rays

An exciting new area of research is the X-ray laser. X-ray lasers already exist, but they are not yet practical devices. Some experimental versions fill a complete building. Scientists in the United States, Great Britain, France, Germany, Russia, China, and Japan have been working on various designs for years, and they seem undaunted by the technical difficulties that must be overcome.

An X-ray laser microscope would give biologists a new research tool. Conventional microscopes are limited by the wavelength of visible light, which is a thousand times longer than that of X-rays. Electron microscopes can approach X-rays in their ability to distinguish detail, but the specimen must be stained, dead, and mounted on a slide. The X-rays from a laser could penetrate living cells permitting holographic 3-D photos to be taken of structures within the cell's plasma. Details could be resolved to a billionth of a meter.

X-ray lasers might also etch electronic circuits one-thousandth the size of those being made today. Ω

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